

ALICE potential for heavy-flavour physics

A Dainese

INFN - Laboratori Nazionali di Legnaro, viale dell'Università 2, 35020 Legnaro (Padova), Italy. e-mail: andrea.dainese@lnl.infn.it

Abstract. The Large Hadron Collider (LHC), where lead nuclei will collide at the unprecedented c.m.s. energy of 5.5 TeV per nucleon–nucleon pair, will offer new and unique opportunities for the study of the properties of strongly interacting matter at high energy density over extended volumes. We will briefly explain why heavy-flavour particles are well-suited tools for such a study and we will describe how the ALICE experiment is preparing to make use of these tools.

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1. Introduction

ALICE [1,2] is the dedicated heavy-ion experiment at the Large Hadron Collider (LHC). The main physics goal of the experiment is the study of strongly-interacting matter in the conditions of high energy density ($> 10 \text{ GeV/fm}^3$) and high temperature ($\gtrsim 0.2 \text{ GeV}$), expected to be reached in central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.5 \text{ TeV}$. Under these conditions, according to lattice QCD calculations, quark confinement into colourless hadrons should be removed and a deconfined Quark–Gluon Plasma should be formed [1].

As we will detail in the next section, heavy-flavour particles are regarded as effective probes of the system conditions. In particular:

- open charm and beauty hadrons would be sensitive to the energy density, through the mechanism of in-medium energy loss of heavy quarks;
- quarkonium states would be sensitive to the initial temperature of the system through their dissociation due to colour screening.

2. Heavy-quark and quarkonia phenomenology at the LHC

The expected yields for heavy-quark production in pp collisions at $\sqrt{s} = 14 \text{ TeV}$ are reported in the first line of Table 1 [3], as obtained from the next-to-leading order perturbative QCD calculation implemented in the MNR program [4] with *reasonable* parameter values (quark masses and perturbative scales) [3]. These yields have large uncertainties, of about a factor 2, estimated by varying the parameters [3]. In the table we report also the $c\bar{c}$ and $b\bar{b}$ yields in central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.5 \text{ TeV}$, obtained including in the calculation the nuclear modification of the parton distribution

Table 1. Expected $Q\bar{Q}$ yields at the LHC, from NLO pQCD [3]. For Pb–Pb, nuclear shadowing of the parton distribution functions is included and binary scaling is applied.

colliding system	$\sqrt{s_{\text{NN}}}$	centrality	$N^{c\bar{c}}/\text{event}$	$N^{b\bar{b}}/\text{event}$
pp	14 TeV	minimum bias	0.16	0.0072
Pb–Pb	5.5 TeV	central (0–5% σ^{tot})	115	4.6

functions (EKS98 parametrization [5]) and applying a scaling of the hard yields with the mean number $\langle N_{\text{coll}} \rangle$ of binary nucleon–nucleon collisions in the Pb–Pb collision.

Experiments at the Relativistic Heavy Ion Collider (RHIC) have shown that the nuclear modification factor of particles p_t distributions, $R_{\text{AA}}(p_t, \eta) = \frac{1}{\langle N_{\text{coll}} \rangle} \cdot \frac{d^2 N_{\text{AA}}/dp_t d\eta}{d^2 N_{\text{pp}}/dp_t d\eta}$, is a sensitive observable for the study of the interaction of the hard partons with the medium produced in nucleus–nucleus collisions. Heavy quark medium-induced quenching is one of the most captivating topics to be addressed in Pb–Pb collisions at the LHC. Due to the QCD nature of parton energy loss, quarks are predicted to lose less energy than gluons (that have a higher colour charge) and, in addition, the ‘dead-cone effect’ is expected to reduce the energy loss of massive quarks with respect to light partons [6, 7]. Therefore, one should observe a pattern of gradually decreasing R_{AA} suppression when going from the mostly gluon-originated light-flavour hadrons (h^\pm or π^0) to D and to B mesons [8]: $R_{\text{AA}}^h \lesssim R_{\text{AA}}^D \lesssim R_{\text{AA}}^B$. The enhancement, with respect to unity, of *heavy-to-light* R_{AA} ratios has been suggested [8] as a sensitive observable to test the colour-charge ($R_{D/h} = R_{\text{AA}}^D/R_{\text{AA}}^h$) and mass ($R_{B/h} = R_{\text{AA}}^B/R_{\text{AA}}^h$) dependence of parton energy loss. In addition, the smaller predicted energy loss of b quarks may allow to overcome the main limitation of light partons as probes of the medium, namely their low sensitivity to the density of the medium. According to the theoretical models [9] based on the BDMPs framework [10], this so-called ‘fragility’ became apparent already in Au–Au collisions at RHIC, and would be more pronounced in Pb–Pb collisions at the LHC, where hard gluons would either be absorbed in the medium or escape the medium without really probing its density. Beauty quarks could instead provide stringent constraints on the energy density of the medium.

The measurement of D and B meson production cross sections will also serve as a baseline for the study of medium effects on quarkonia. Two of the most interesting items in the quarkonia sector at the LHC will be: (a) understanding the interplay between colour-screening-induced suppression and statistical regeneration for J/ψ production in a medium containing on the order of 100 $c\bar{c}$ pairs (see Table 1); (b) measuring for the first time medium effects on the bottomonia resonances, expected to be available with sufficient yields at the LHC. On this point, the predicted suppression pattern as a function of the plasma temperature is particularly interesting: the Υ would melt at $T \approx 0.42$ GeV, a temperature that would be reached only at the LHC, while the Υ' would melt at the same temperature as the J/ψ , $T \approx 0.19$ GeV. It will thus be important for the experiments to be able to measure also the Υ' , because, at variance

with the J/ψ , it is expected to have a small regeneration probability and it would be very useful to disentangle J/ψ suppression and regeneration. In summary, measuring the in-medium dissociation probability of the different quarkonium states at the LHC will provide an estimate of the initial medium temperature. We note that, in order to study the medium effects on charmonia, it will be mandatory to measure the fraction of secondary charmonia from B decays, expected to be about 20% for the J/ψ , in absence of medium-induced effects.

3. Heavy-flavour detection in ALICE

The design of the ALICE apparatus [1] will allow the detection of open heavy-flavour hadrons and quarkonia in the high-multiplicity environment of central Pb–Pb collisions at LHC energy, where up to few thousand charged particles might be produced per unit of rapidity. The heavy-flavour capability of the ALICE detector is provided by:

- Tracking system; the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Transition Radiation Detector (TRD), embedded in a magnetic field of 0.5 T, allow track reconstruction in the pseudorapidity range $|\eta| < 0.9$ with a momentum resolution better than 2% for $p_t < 20$ GeV/ c and a transverse impact parameter[‡] resolution better than 60 μm for $p_t > 1$ GeV/ c (the two innermost layers of the ITS are equipped with silicon pixel detectors).
- Particle identification; charged hadrons (π , K, p) are separated via dE/dx in the TPC and in the ITS and via time-of-flight measurement in the Time Of Flight (TOF) detector; electrons are separated from charged pions in the dedicated Transition Radiation Detector (TRD), and in the TPC; muons are identified in the forward muon spectrometer covering in acceptance the range $-4 < \eta < -2.5$.

Simulation studies [2] have shown that ALICE has good potential to carry out a rich heavy-flavour physics programme. The main analyses in preparation are:

- Open charm (section 4): fully reconstructed hadronic decays $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow K^-\pi^+\pi^+$ (under study), $\Lambda_c^+ \rightarrow pK^-\pi^+$ (under study) in $|\eta| < 0.9$.
- Open beauty (section 4 and Ref. [11]): inclusive single leptons $B \rightarrow e + X$ in $|\eta| < 0.9$ and $B \rightarrow \mu + X$ in $-4 < \eta < -2.5$; inclusive displaced charmonia $B \rightarrow J/\psi (\rightarrow e^+e^-) + X$ (under study).
- Quarkonia (section 5): ψ and Υ states in the e^+e^- ($|\eta| < 0.9$) and $\mu^+\mu^-$ ($-4 < \eta < -2.5$) channels.

For all studies, a multiplicity of $dN_{\text{ch}}/dy = 4000\text{--}6000$ was assumed for central Pb–Pb collisions. In the following, we report the results corresponding to the expected statistics collected by ALICE per LHC year: 10^7 central (0–5% σ^{inel}) Pb–Pb events at $\mathcal{L}_{\text{Pb–Pb}} = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ and 10^9 pp events at $\mathcal{L}_{\text{pp}}^{\text{ALICE}} = 5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$, in the barrel detectors; the forward muon arm will collect about 40 times larger samples (i.e. 4×10^8 central Pb–Pb events).

[‡] The transverse impact parameter, d_0 , is defined as the distance of closest approach of the track to the interaction vertex, in the plane transverse to the beam direction.

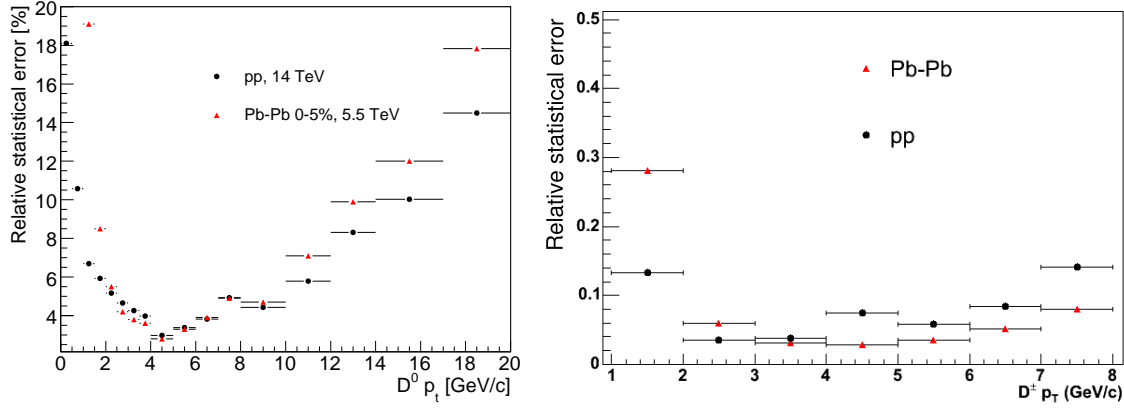


Figure 1. Expected relative statistical errors for the measurement in ALICE of the production cross sections of D^0 in the $K^-\pi^+$ channel (left) and D^+ in the $K^-\pi^+\pi^+$ channel (right), in 0–5% central Pb–Pb collisions and in pp collisions.

4. Open charm and beauty capabilities

Exclusive charm meson reconstruction. Among the most promising channels for open charm detection are the $D^0 \rightarrow K^-\pi^+$ ($c\tau \approx 120 \mu\text{m}$, branching ratio $\approx 3.8\%$) and $D^+ \rightarrow K^-\pi^+\pi^+$ ($c\tau \approx 300 \mu\text{m}$, branching ratio $\approx 9.2\%$) decays. The detection strategy to cope with the large combinatorial background from the underlying event is based on the selection of displaced-vertex topologies, i.e. separation from the primary vertex of the tracks from the secondary vertex and good alignment between the reconstructed D meson momentum and flight-line [2, 12]. An invariant-mass analysis is used to extract the raw signal yield, to be then corrected for selection and reconstruction efficiency and for detector acceptance. As shown in Fig. 1 (left), the accessible p_t range for the D^0 is 1–20 GeV/c in Pb–Pb and 0.5–20 GeV/c in pp, with statistical errors better than 15–20% at high p_t . Similar capability is expected for the D^+ (right-hand panel), though at present the statistical errors are estimated only in the range $1 < p_t < 8$ GeV/c. The systematic errors (acceptance and efficiency corrections, centrality selection for Pb–Pb) are expected to be smaller than 20%.

Beauty via single electrons. The main sources of background electrons are: decays of D mesons; π^0 Dalitz decays and decays of light vector mesons (e.g. ρ and ω); conversions of photons in the beam pipe or in the inner detector layer and pions misidentified as electrons. Given that electrons from beauty have average impact parameter $d_0 \simeq 500 \mu\text{m}$ and a hard p_t spectrum, it is possible to obtain a high-purity sample with a strategy that relies on: electron identification with a combined dE/dx (TPC) and transition radiation (TRD) selection; impact parameter cut to reduce the charm-decay component and reject misidentified π^\pm and e^\pm from Dalitz decays and γ conversions. As an example, with $d_0 > 200 \mu\text{m}$ and $p_t > 2$ GeV/c, the expected statistics of electrons from b decays is 8×10^4 for 10^7 central Pb–Pb events, allowing the measurement of electron-level p_t -

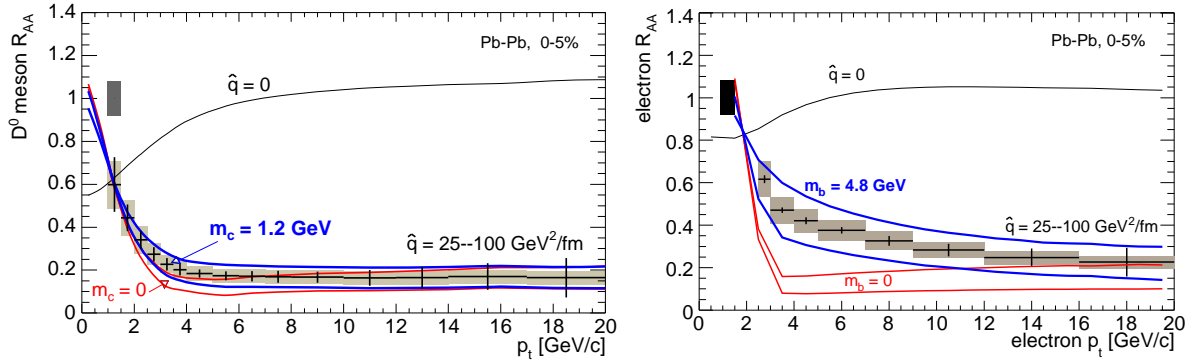


Figure 2. Nuclear modification factors for D^0 mesons (left) and for B-decay electrons (right). Errors corresponding to the centre of the prediction bands for massive quarks are shown: bars = statistical, shaded area = systematic.

differential cross section in the range $2 < p_t < 20$ GeV/ c with statistical errors smaller than 15% at high p_t . Similar performance figures are expected for pp collisions [11].

Beauty via muons. B production in Pb–Pb collisions can be measured also in the ALICE muon spectrometer ($-4 < \eta < -2.5$) analyzing the single-muon p_t distribution [2]. The main backgrounds to the ‘beauty muon’ signal are π^\pm , K^\pm and charm decays. The cut $p_t > 1.5$ GeV/ c is applied to all reconstructed muons in order to increase the signal-to-background ratio. Then, a fit technique allows to extract a p_t distribution of muons from B decays. Since only minimal cuts are applied, the statistical errors are expected to be smaller than 5% up to muon $p_t \approx 30$ GeV/ c [11].

Nuclear modification factors. We investigated the possibility of using the described charm and beauty measurements to study the high- p_t suppression induced by parton energy loss. The sensitivity to R_{AA}^D and $R_{AA}^{e \text{ from B}}$ is presented in Fig. 2. Predictions [8] with and without the effect of the heavy-quark mass, for a medium transport coefficient \hat{q} (a measurement of the medium density) in the range 25–100 GeV²/fm, are also shown.

5. Quarkonia capabilities

ALICE can detect quarkonia in the dielectron channel at central rapidity ($|y| \lesssim 1$) and in the dimuon channel at forward rapidity ($-4 \lesssim y \lesssim -2.5$). In both channels the acceptance extends down to zero transverse momentum, since the minimum p_t for e and μ identification is about 1 GeV/ c . The high p_t reach is expected to be 10 (20) GeV/ c for the J/ψ in e^+e^- ($\mu^+\mu^-$), for a Pb–Pb run of one month at nominal luminosity. We emphasized the importance of separating the Υ and Υ' , to probe the initial temperature of the medium; given that the mass difference between the two bottomonium states is about 500 MeV, a mass resolution of order 100 MeV at $M_{\ell+\ell-} \sim 10$ GeV, i.e. $\sigma_M/M \approx 1\%$, is required. This requirement is fulfilled for both dielectrons and dimuons, with a mass resolution of about 90 MeV. For illustration, in Fig. 3 we show the simulated dilepton mass spectra in the Υ region after background subtraction [2].

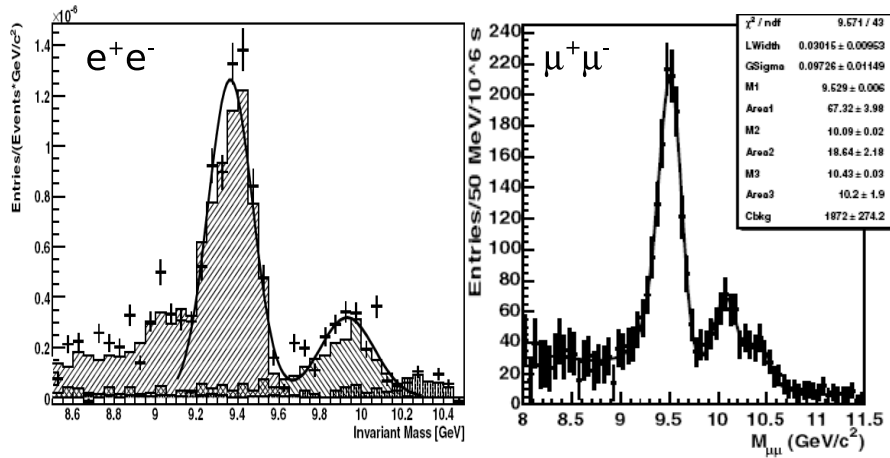


Figure 3. The signal of Υ states in central Pb-Pb collisions, as reconstructed by ALICE [2], in the dielectron and in the dimuon channel, in one month of data-taking.

Simulation studies are in progress to prepare a measurement of the fraction of J/ψ that feed-down from B decays. Such measurement can be performed by studying the separation of the dilepton pairs in the J/ψ invariant mass region from the main interaction vertex. The analysis is also expected to provide a measurement of the beauty p_t -differential cross section.

6. Summary

We have discussed how heavy quarks, abundantly produced at LHC energies, will allow to address several issues at the heart of in heavy-ion physics. They provide tools to probe the density (via parton energy loss and its predicted mass dependence) and the temperature (via successive dissociation patterns of quarkonia) of the high-density QCD medium formed in Pb-Pb collisions. The excellent tracking, vertexing and particle identification performance of ALICE will allow to fully explore this rich phenomenology.

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